

# Charge splitting of directed flow and space-time picture of pion emission from the electromagnetic interactions with spectators

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## Abstract

We estimate the effect of the spectator-induced electromagnetic interaction on the directed flow of charged pions. For intermediate centrality Au+Au collisions at  $\sqrt{s_{NN}} = 7.7$  GeV, we demonstrate that the electromagnetic interaction between spectator charges and final state pions results in charge splitting of positive and negative pion directed flow. Such a charge splitting is visible in the experimental data reported by the STAR Collaboration.

The magnitude of this charge splitting appears to strongly depend on the actual distance between the pion emission site (pion at freeze-out) and the spectator system. As such, the above electromagnetic effect brings new, independent information on the space-time evolution of pion production in heavy ion collisions.

From the comparison of our present analysis to our earlier studies made for pions produced at higher rapidity, we formulate conclusions on the rapidity dependence of the distance between the pion emission site and the spectator system. This distance appears to decrease with increasing pion rapidity, reflecting the longitudinal expansion of the strongly-interacting system responsible for pion emission. Thus for the first time, information on the space-time characteristics of the system is being provided by means of the spectator-induced electromagnetic interaction.

The above electromagnetic effect being in fact a straight-forward consequence of the presence of spectator charges in the collision, we consider that it should be considered as a baseline for studies of other phenomena, like those related to the electric conductivity of the quark-gluon plasma.

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## I. INTRODUCTION

Electromagnetic properties of heavy ion collisions, and in particular phenomena related to the presence of strong EM fields in the course of the nucleus-nucleus reaction, attract an evident interest in the community. While a large number of inspiring papers could be cited here, only two will be addressed below, as two different but highly interesting examples. Firstly, a proposal for the estimation of the electric conductivity of the quark gluon plasma, by using the electric field resulting from the charge difference between the colliding Cu and Au nuclei was made by Hirono, Hongo and Hirano [1]. Secondly, a study of electric currents acting in the QGP, and induced by the magnetic fields present in Au+Au and Pb+Pb reactions, recently became available from Gürsoy, Kharzeev and Rajagopal [2]. In both cases, the sensitivity of azimuthal asymmetries in particle emission, and in particular directed flow<sup>1</sup>  $v_1 \equiv \langle \cos(\phi - \Psi_{\text{RP}}) \rangle$ , to electromagnetic phenomena acting in heavy ion collisions was pointed out by the authors.

This corroborates with the results of our recent work on peripheral Pb+Pb collisions [3], where the influence of the electromagnetic interaction between the spectator systems and the charged final state pions was quantified. Our work demonstrated that this interaction could induce sizeable values of directed flow, and could be used as a new source of information on the space-time evolution of pion production. This finding was quite similar to what we established earlier for  $\pi^+/\pi^-$  ratios at high values of rapidity [4].

Electromagnetic effects on particle emission clearly imply the dependence of specific observables on particle charge, in particular also for particles of the same mass (like e.g.  $\pi^+$  and  $\pi^-$  mesons). Such a charge dependence for specific components of pion directed flow was indeed predicted in [1, 2], as well as by us in [3]. In this context, the importance of experimental data on directed flow measured *separately* for positive and negative pion charges ( $v_1^{\pi^+}$ ,  $v_1^{\pi^-}$ ) becomes clearly evident. Such data is still, at the present moment, rather scarce.

The STAR Collaboration [5] is, to the best of our knowledge, the first and unique experimental group in high energy heavy ion physics to provide such data simultaneously for positively and negatively charged pions<sup>2</sup>. Final data of the STAR Collaboration on the directed flow of protons, antiprotons and pions in the Au+Au collision energy range from  $\sqrt{s_{NN}} = 7.7$  up to 200 GeV have recently been published [6]. These include measurements of  $v_1$  for  $p$ ,  $\bar{p}$ ,  $\pi^+$  and  $\pi^-$ , made altogether for seven collision energies in the c.m.s. rapidity range of  $|y| < 1$ . Specifically, at lower values of  $\sqrt{s_{NN}}$  the comparison of positive and negative pion directed flow in intermediate centrality (10-40%) Au+Au collisions displays a splitting of  $v_1^{\pi^+}$  and  $v_1^{\pi^-}$ , with  $v_1^{\pi^+} < v_1^{\pi^-}$  at positive rapidity. As remarked both in [2] and by us in [3], this is consistent with the expectation of a specific charge-dependent component of directed flow, induced by electromagnetic effects. While already in [3], we stated our idea of this effect being caused by the spectator-induced EM field, we feel that a more in-depth verification of this hypothesis is in place. It is indeed of importance to verify whether the electromagnetic interaction between spectator charges and *final state* pions can have the

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<sup>1</sup> Note:  $\phi$  denotes the emitted particle's azimuthal angle while  $\Psi_{\text{RP}}$  gives the orientation of the reaction plane.

<sup>2</sup> We note the existence of the data on directed and elliptic flow of (exclusively) positive pions near target rapidity measured by the WA98 experiment [7], many years prior to the data from the STAR Collaboration. We also note the presence of STAR measurements on elliptic flow [8]; this was also made separately for particles of different charges including  $\pi^+$  and  $\pi^-$ .

right magnitude to explain the observed splitting of  $v_1^{\pi^+}$  and  $v_1^{\pi^-}$ , and, if this is indeed the case, to establish what conclusions can be drawn on that basis for the space-time evolution of the collision dynamics. This is even more important in view of the predictions made in [2] of the link between charged currents in the quark gluon plasma and the charge splitting of directed flow. The relatively straight-forward electromagnetic effect on final state pions studied by us can indeed be considered as a *baseline* for these more untrivial phenomena related to the electric conductivity of the QGP.

In this context, the aim of the present paper is to estimate the effect of the spectator-induced electromagnetic field on the directed flow of charged final state pions. The study presented here is made for the specific case of pions produced in the c.m.s. rapidity range  $|y| < 1$  corresponding to the STAR data [6], in intermediate centrality Au+Au collisions. We focus on the lowest STAR energy of  $\sqrt{s_{NN}} = 7.7$  GeV where the effect of charge splitting of directed flow is found to be largest.

The remainder of this paper is organized as follows. The discussion of the charge splitting apparent in STAR data is made in section II. The description of our numerical Monte Carlo tool, used to estimate the electromagnetic component of directed flow, is presented in section III. The results of our Monte Carlo simulation, as well as their comparison to the STAR data, are discussed in section IV. In section V, we compare our results with these coming from our earlier studies, and comment on other effects that could induce charge-dependent pion directed flow. Our conclusions are summarized in section VI.

## II. EXPERIMENTAL DATA FROM STAR

The results of the STAR Collaboration on charged pion directed flow in Au+Au collisions at  $\sqrt{s_{NN}} = 7.7$  GeV are shown in Fig. 1. The numerical values from [6] are redrawn as a function of the scaled pion rapidity,  $y/y_{\text{beam}}$ , where  $y_{\text{beam}}$  is the rapidity of the incoming nucleus in the collision c.m. system. We decide on this scaled variable for an easier comparison with other collision energies, including our results from [3] (see also discussions made in [9, 10]). As specified in [6], the presented experimental data are obtained within a lower cut on pion transverse momentum,  $p_T > 0.2$  GeV/c, and an upper cut on pion total momentum,  $p < 1.6$  GeV/c. Three facts are immediately apparent from the figure:

1. At this relatively low collision energy, the STAR data points cover a very appreciable region in  $y/y_{\text{beam}}$ .
2. Apart from the dominant and well-known trend of a smooth decrease with increasing rapidity, the data points clearly display a pronounced split of  $v_1$  for  $\pi^+$  and  $\pi^-$ .
3. A minor deviation from antisymmetry about mid-rapidity is visible for the data points, in particular at the edges of the covered kinematical range. Following the detailed discussion made in [6], we regard this simply as an experimental uncertainty.

In order to get hold of electromagnetic effects on directed flow, we assume that the total values of positive and negative pion  $v_1$  can be approximated by the sum of two terms:

$$v_1^{\pi^+} \approx v_1^{\text{flow}} + v_1^{\pi^+, EM} , \quad (2.1)$$

$$v_1^{\pi^-} \approx v_1^{\text{flow}} + v_1^{\pi^-, EM} . \quad (2.2)$$

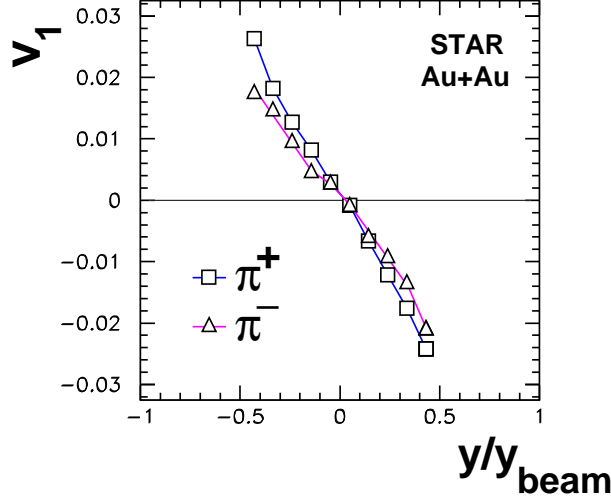


FIG. 1: (Color online) Directed flow  $v_1$  of positive and negative pions in intermediate centrality (10-40%) Au+Au collisions at  $\sqrt{s_{NN}} = 7.7$  GeV. The data points in the figure are redrawn from [6]. The plotted error bars are statistical only, and remain below symbol size.

where the first, dominant, charge-independent term  $v_1^{flow}$  corresponds to the total directed flow imposed by the strong interaction (e.g., by the hydrodynamical evolution of the system), while the second, smaller and charge-dependent term  $v_1^{\pi^+,EM}$  ( $v_1^{\pi^-,EM}$ ) is induced by electromagnetic interactions. The approximate additivity postulated in (2.1) and (2.2) was verified by Monte Carlo calculations, somewhat simplified but similar to these described in section III.

From our earlier studies [3], as well as from Monte Carlo simulations performed for the present work (section IV), we know that in the range of rapidity considered here, the spectator-induced electromagnetic component of directed flow is, at least to a good approximation, opposite for opposite charges. Thus we postulate:

$$v_1^{\pi^+,EM} \approx -v_1^{\pi^-,EM} . \quad (2.3)$$

By solving (2.1)-(2.3), we conclude that the electromagnetic component of the directed flow presented in Fig. 1 can be obtained as:

$$v_1^{\pi^+,EM} \approx \frac{1}{2}(v_1^{\pi^+} - v_1^{\pi^-}) , \quad (2.4)$$

$$v_1^{\pi^-,EM} \approx -\frac{1}{2}(v_1^{\pi^+} - v_1^{\pi^-}) . \quad (2.5)$$

This is shown in Fig. 2. The resulting values of  $v_1^{\pi^+,EM}$  and  $v_1^{\pi^-,EM}$  consistently reach up to about 0.002, with the exception of one asymmetric outlier visible at the low edge of the covered kinematical range. This we regard as an experimental uncertainty as specified in point 3. above. We conclude that the overall precision of the STAR data is sufficient to identify the - relatively small - electromagnetic component of directed flow. As we will demonstrate in the subsequent parts of this paper, the magnitude of this electromagnetic component (Fig. 2) provides information on the space-time evolution of the process of pion production in Au+Au collisions at central rapidities.

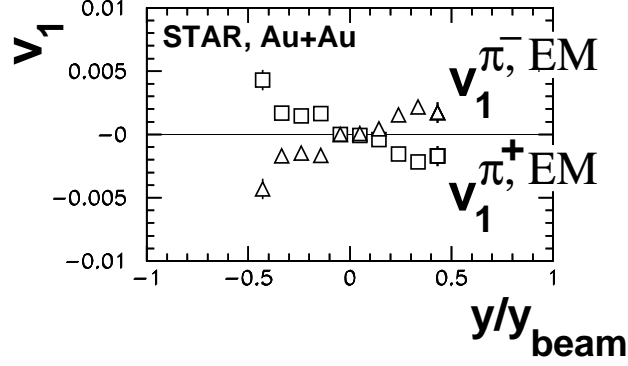


FIG. 2: Electromagnetically-induced directed flow for positive pions (squares) and for negative pions (triangles), obtained from (2.4)-(2.5). The plotted error bars are statistical only.

### III. CALCULATING THE ELECTROMAGNETICALLY-INDUCED DIRECTED FLOW

We now turn to the description of our Monte Carlo method of estimating the part of charged pion directed flow induced by the electromagnetic interaction between final state pions and the two spectator systems. Our approach is essentially similar to that taken in our precedent works [3, 4], where a more detailed description can be found. Only the aspects relevant for the present analysis will be discussed here.

Our aim is to provide a realistic estimate of spectator-induced electromagnetic effects on charged pion directed flow. At the same time, we wish to avoid a detailed discussion of the complex, poorly known mechanisms governing the dynamics of the Au+Au reaction. For this reason our approach is maximally simplified as explained below:

- (a) We assume that the Au+Au collision takes place at a given impact parameter  $b$ , corresponding to the STAR sample of intermediate centrality reactions. This is illustrated in Fig. 3. The two spectator systems are approximated by homogeneous, Lorentz-contracted spheres, which follow their initial path with essentially unchanged velocities. The reaction plane is defined by the collision axis and by the impact parameter vector  $\vec{b}$ .
- (b) Charged pions ( $\pi^+$ ,  $\pi^-$ ) are assumed to be emitted from a single point in space (the original interaction point) and in a single moment in time ( $t = t_E$ ). The resulting initial distance  $d_E$  between the pion emission site and the two spectator systems is the unique free parameter of our simulation. For consistency with our precedent works this quantity will be expressed in terms of the reduced distance  $D_E \equiv d_E/\beta$ , where  $\beta$  is the spectator velocity<sup>3</sup>. We note that at  $\sqrt{s_{NN}} = 7.7$  GeV the two quantities are equal within three percent.
- (c) The initial  $(y, p_T)$  distribution of the emitted pions (before the action of the electromagnetic field) is assumed to be similar to underlying nucleon-nucleon collisions and to obey wounded nucleon scaling [11]. Full azimuthal symmetry is assumed for these initially emitted pions.

<sup>3</sup> For simplicity we set the velocity of light  $c = 1$  in the entire paper.

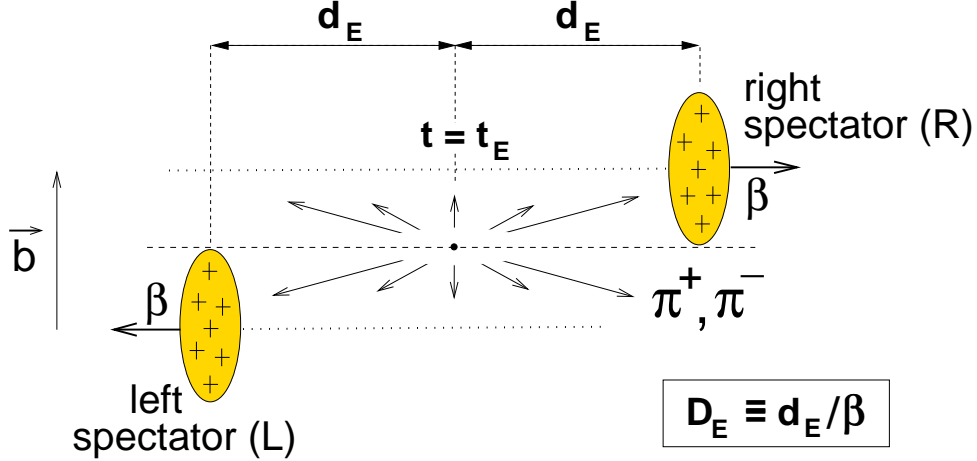


FIG. 3: (Color online) Our simplified picture of the Au+Au collision at  $\sqrt{s_{NN}} = 7.7$  GeV.

- (d) The emitted charged pions are then numerically traced in the electromagnetic field induced by the spectator charges, until they reach a distance of 10,000 fm away from the original interaction point and from each of the two spectator systems. Spectator fragmentation is neglected. Effects induced by the participant charge, strong final state interactions, etc, are not considered.

Several clarifications must be added to points (a)-(d) above.

- (a) *Geometry of the Au+Au collision.* The centrality of the STAR data [6] was defined by the number of charged particles emitted in the region of pseudorapidity  $|\eta| < 0.5$ . For consistency, in the present work the number of participating nucleons  $n_{part}$  was obtained by extrapolating the results of Glauber Monte Carlo calculations made with the same definition of centrality as above, in the range of  $\sqrt{s_{NN}}$  from 20 to 200 GeV [12]. For intermediate centrality (10-40%) Au+Au collisions, the extrapolation down to  $\sqrt{s_{NN}} = 7.7$  GeV gave the mean number of participants of about 166. The other geometrical characteristics of the collision have been estimated by means of a dedicated geometrical Monte Carlo simulation, discussed in detail in [4]. This used the  $^{197}\text{Au}$  Woods-Saxon density profile taken from [12] and assumed the elementary nucleon-nucleon cross-section equal to 30.6 mb, in agreement with existing data [13]. On that basis, the geometrical impact parameter corresponding to 166 participants was found to be  $b_{geom} = 7.09$  fm. The center of gravity of each of the two spectator systems was found to be displaced by  $\Delta b = 2.00$  fm relative to that of the original Au nucleus. The average spectator charge was found to be  $Q = 45.7$  elementary units. After inspecting the spectator shape resulting from our geometrical simulation, and considering its exact shape as unimportant for our present analysis, we modelled the two spectator systems as two homogeneously charged spheres. The sphere density was the standard nuclear density  $\rho = 0.17/\text{fm}^3$  in the rest frame of each sphere. The center of each sphere was displaced by 2.00 fm in order to match the center of gravity of the spectator system. As a result, our effective impact parameter (distance of closest approach between the two sphere's centers) was  $b = b_{geom} + 2\Delta b = 11.1$  fm.
- (b) *Pion emission.* As this will be shown in section IV, our maximal simplification of initial conditions determining pion emission (i.e., the reduction of the emission zone

to a single point in space and in time) gives a convenient way to estimate the sensitivity of the electromagnetic component of directed flow to the space-time evolution of the heavy ion reaction. In the present work, we will mostly focus on its sensitivity to the distance between the emitted pions and the spectator system as indicated in Fig. 3.

- (c) *Initial distribution of emitted pions.* We consider that the exact shape of the kinematical distribution of emitted pions has only a small influence on the electromagnetic component of  $p_T$ -integrated directed flow. On the other hand, the very nature of the spectator-induced electromagnetic interaction (acting on the pion  $x, y, z$  trajectory over a sizeable period of time) implies the need for a reasonable parametrization of this distribution in terms of the complete momentum vector defined, e.g., by three variables  $(y, p_T, \phi)$ . As a result, we assume the pion  $(y, p_T)$  distribution to be similar to that in nucleon-nucleon events scaled up by the number of participant (wounded) nucleons. We describe it by means of an analytical parametrization of average pion  $\left(\frac{\pi^+ + \pi^-}{2}\right)$  spectra in p+p collisions, obtained by the NA49 experiment at  $\sqrt{s_{NN}} = 17.3$  GeV [14]. A precise description of this parametrization is given in [4]. The NA49 data are expressed in terms of the Feynman variable  $x_F = 2p_L/\sqrt{s}$  and of transverse momentum  $p_T$ , and cover the region from  $x_F = 0$  to 0.85 and from  $p_T = 0$  to 2.1 GeV/c in the collision c.m.s. This is more than sufficient for the present study, defined by the more restricted coverage of the experimental STAR data discussed in section II. For simplicity, distributions of positively and negatively charged pions are assumed to be identical. Feynman scaling in  $x_F$  [15], and similarity of  $p_T$ -spectra are assumed from  $\sqrt{s_{NN}} = 17.3$  GeV down to 7.7 GeV.

The aim of the present work being to estimate only the *electromagnetic component* of directed flow ( $v_1^{\pi^+, EM}$  and  $v_1^{\pi^-, EM}$  from Eqs. 2.1 and 2.2), the present simulation assumes full azimuthal symmetry in initial pion emission before the action of the electromagnetic field. As such, all the results presented in section IV will correspond to directed flow induced exclusively by the electromagnetic interaction.

- (d) *Propagation of pions in the electromagnetic field.* Our numerical treatment of the motion of charged pions in the electromagnetic field induced by the two spectator systems was explained in detail in [4]. A concise description can also be found in [3]. Generally, the purely electrostatic fields of the two spectators in their respective rest frames (these we will denote as  $\vec{E}'_L$  for the “left” spectator and  $\vec{E}'_R$  for the “right” spectator from Fig. 3) are transformed to the overall collision c.m.s. This results in the emergence of both electric and magnetic fields. For the “left” spectator one writes:

$$\begin{aligned}\vec{E}_L &= \gamma \vec{E}'_L - \frac{\gamma^2}{\gamma + 1} \vec{\beta}_L \left( \vec{\beta}_L \cdot \vec{E}'_L \right) , \\ \vec{B}_L &= \gamma \left( \vec{\beta}_L \times \vec{E}'_L \right) .\end{aligned}\tag{3.1}$$

In the equations above,  $\vec{\beta}_L$  is the vector of velocity of the “left” spectator ( $|\vec{\beta}_L| = \beta$  in Fig. 3) and  $\gamma = (1 - \beta^2)^{-1/2}$ . Analogous equations can be written for the “right” spectator, yielding the two corresponding fields  $\vec{E}_R$  and  $\vec{B}_R$  in the nucleus-nucleus collision c.m.s. The Lorentz force  $\vec{F}_\pi$  acting on the pion results from the combined action of electric and magnetic fields:

$$\frac{d\vec{p}_\pi}{dt} = \vec{F}_\pi = q_\pi \left( \vec{E} + \vec{\beta}_\pi \times \vec{B} \right) ,\tag{3.2}$$

where  $\vec{p}_\pi$  and  $\vec{\beta}_\pi$  are the pion momentum and velocity vectors,  $q_\pi$  is the pion charge, while  $\vec{E} = \vec{E}_L + \vec{E}_R$  and  $\vec{B} = \vec{B}_L + \vec{B}_R$  are standard superpositions of fields from the two sources. The pion trajectory  $\vec{r}_\pi(t)$  is given by the classical relativistic equation of motion:

$$\frac{d\vec{r}_\pi}{dt} = \vec{\beta}_\pi = \frac{\vec{p}_\pi}{\sqrt{p_\pi^2 + m_\pi^2}}, \quad (3.3)$$

where  $m_\pi$  is the pion mass, and the pion momentum  $\vec{p}_\pi$  is obtained from Eq. (3.2). Our approach explained above takes account of relativistic effects, including in particular also retardation [16]. Technically, the propagation of the charged pion in the electromagnetic field is performed numerically, by means of an iterative procedure made in small steps in time. This is done with variable step size which depends on the actual distance of the pion from the nearest spectator system. The iteration proceeds until the pion is at least 10,000 fm away from the interaction point and from each of the two spectator systems in their respective rest frames. We note that negative pions, which do not escape from the potential well induced by the spectator system are rejected and do not enter into our final state distributions.

## IV. RESULTS

This section contains the discussion of results of our simulation of electromagnetically-induced directed flow, caused by the electromagnetic interaction between the spectator systems and charged final state pions. These results will be compared to the charge-dependent part of the pion directed flow measured by the STAR experiment.

All the Monte Carlo results presented here have been obtained for intermediate centrality Au+Au collisions at  $\sqrt{s_{NN}} = 7.7$  GeV, following the procedure described in section III. They are integrated over transverse momentum  $p_T$  in the range from 0.2 to 1.6 GeV/c. It has been verified that these results will practically not change when applying the cut on total momentum  $p < 1.6$  GeV/c actually used for the STAR data (section II) instead of the upper cut on  $p_T$ . Thus the results of the simulation are directly comparable to the values extracted from experimental data.

We remind that as it is described in section III, the presented Monte Carlo simulations correspond to effects resulting *exclusively from the electromagnetic interaction*. On purpose, the part of pion directed flow resulting from the strong interaction (denoted  $v_1^{flow}$  in section II) is not included in the simulation. The same should be valid for the charge-dependent part of experimentally observed directed flow, which we extracted from the STAR data in section II, Fig. 2.

Fig. 4 shows the electromagnetically-induced directed flow of positive and negative pions (denoted  $v_1^{\pi^+, EM}$  and  $v_1^{\pi^-, EM}$  as in Eqs. 2.1 and 2.2), simulated assuming six different values of the reduced distance between the pion formation zone and the spectator system:  $D_E = 0, 0.5, 1, 2, 3$ , and 5 fm. Several observations can be made from the Figure:

1. The electromagnetic interaction between final state pions and spectators can result in absolute values of directed flow reaching maximally up to 0.025 in the considered range of rapidity. This is far lower than what we obtained for pions close to beam rapidity, where our prediction for electromagnetically-induced directed flow [3] exceeded absolute values of 0.2, in good agreement with data obtained by the WA98 experiment at the CERN SPS [7].



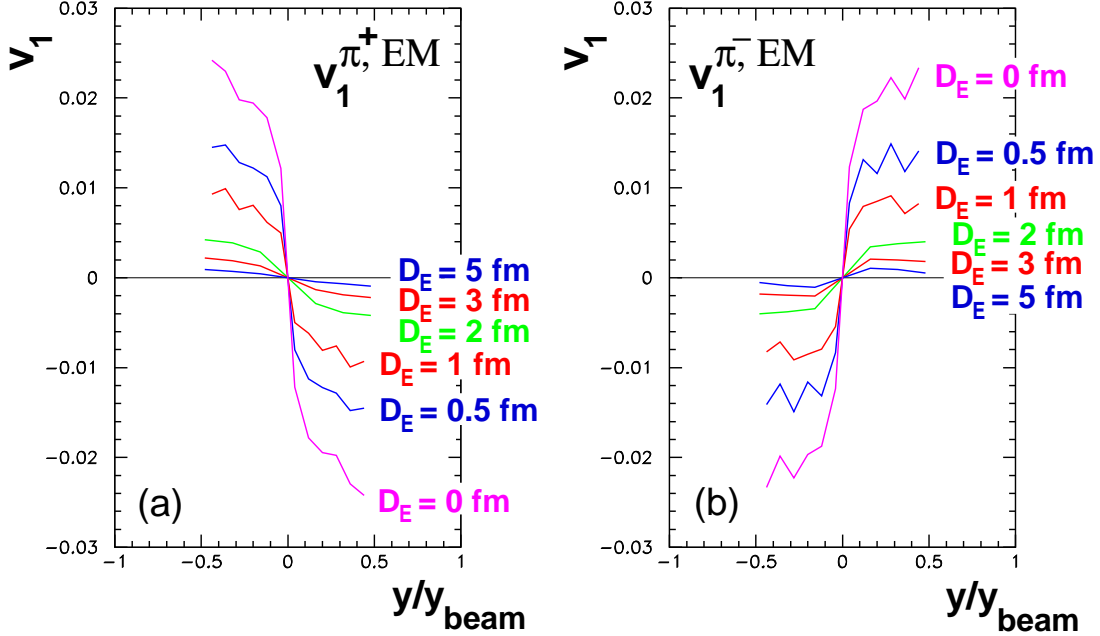


FIG. 4: (Color online) Electromagnetically-induced directed flow of (a) positive and (b) negative pions in intermediate centrality Au+Au collisions at  $\sqrt{s_{NN}} = 7.7$  GeV. The six curves in each panel correspond to six different values of the reduced distance  $D_E$  assumed in the simulation.

2. Nevertheless, the values of  $v_1^{\pi^+, EM}$  and  $v_1^{\pi^-, EM}$  shown in Fig. 4 have to be considered as potentially very sizeable if compared to the *total* values of pion directed flow observed by STAR, Fig. 1. In the extreme case of “immediate” pion production ( $D_E = 0$  fm), the obtained values of  $v_1^{\pi^+, EM}$  would indeed become comparable to total values of  $v_1$  measured by the experiment. This shows that the overall magnitude of the spectator-induced electromagnetic interaction is large enough to exert potentially very important, charge-dependent effects on pion directed flow.
3. At the same time, the electromagnetically-induced directed flow displays a very strong sensitivity to the postulated distance between the pion emission site and the two spectator systems. A change in  $D_E$  of the order of 1 fm results in perfectly visible changes in  $v_1^{\pi^+, EM}$  and  $v_1^{\pi^-, EM}$ ; these changes can exceed 0.01 in the considered range of rapidity. This implies that *the spectator-induced electromagnetic effect on pion directed flow brings new, independent information on the space-time evolution of the system created in the Au+Au collision*, and in particular on the way the emission of final state pions evolves in position space and in time.
4. Specifically, the experimental data from the STAR detector have a sufficient discriminative power to put significant constraints on the postulated space-time scenario of pion emission. This is evident in Fig. 5, where the charge-dependent component of the directed flow measured by the STAR Collaboration clearly appears to favour the value of  $D_E = 3$  fm as the best fit to the data.

We conclude from the above that the magnitude of the electromagnetic interaction between final state pions and the charged spectator systems is largely sufficient to explain the effect

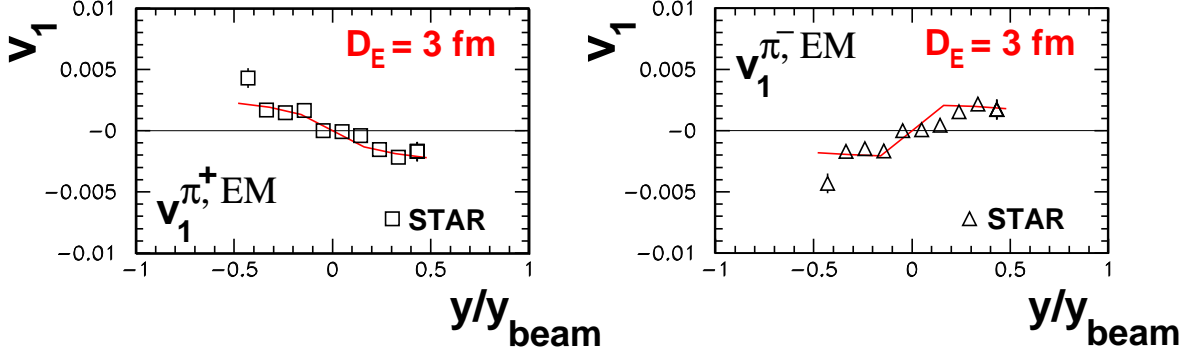


FIG. 5: (Color online) Electromagnetically-induced directed flow of positive pions (left panel) and negative pions (right panel) in intermediate centrality Au+Au collisions at  $\sqrt{s_{NN}} = 7.7$  GeV. The result of our Monte Carlo simulation made assuming  $D_E = 3$  fm (red curve, same as in Fig. 4), is compared to values extracted from the experimental STAR data [6] (data points, same as in Fig. 2).

of charge splitting present in the STAR data from [6]. We also find that a scrutiny of these data in view of the above electromagnetic effect can bring new insight into the space-time evolution of pion production in the nucleus-nucleus reaction. This can constitute a new source of information on the space-time properties of the system created in the heavy ion collision, completely independent from other sources such as pion interferometry.

## V. IMPLICATIONS

Here we will discuss some of the implications of the observations made in section IV. The discussion will address the results of our present analysis, but will also include some of the findings made in our earlier studies of spectator-induced electromagnetic effects on pion directed flow [3] and on  $\pi^+/\pi^-$  ratios [17] in peripheral Pb+Pb collisions at the top SPS energy,  $\sqrt{s_{NN}} = 17.3$  GeV. We will also address some of the issues discussed in Ref. [2].

### A. Pion emission distance as a function of pion rapidity

As it was said in the precedent sections, the unique free parameter in our Monte Carlo simulation is the pion emission distance ( $d_E$  in Fig. 3), namely, the distance between the pion formation zone and the two spectator systems. The comparison of the results of our simulation to electromagnetic effects seen in experimental data (as performed in section IV, Fig. 5 above) allows us to define the *optimal* value of the parameter  $d_E$ , most favoured by the experiment. In spite of the simplicity and of the somewhat effective character of our Monte Carlo study, it is nevertheless interesting to consider how this optimal pion emission distance varies as a function of pion rapidity.

This is made in Table I, where we summarize our findings on the optimal pion emission distance  $d_E$  as they result from the present work and from our earlier studies. Altogether three experimental data sets are considered in the table, see respectively [6], [18], and [7].

We note that for the present analysis,  $d_E \equiv \beta D_E \approx D_E$  as discussed in section III. This gives us  $d_E \approx 3$  fm, as evident from the comparison with the STAR data made in

Ref.	reaction	pion rapidity	observable	exp. data	resulting $d_E$
this work	Au+Au	$-0.5 < y/y_{\text{beam}} < 0.5$	directed flow	STAR [6]	$\approx 3$ fm
[17]	Pb+Pb	$0.64 < y/y_{\text{beam}} < 1.1$	$\pi^+/\pi^-$ ratio	NA49 [18]	$0.5 - 1$ fm
[3]	Pb+Pb	$0.9 < y/y_{\text{beam}} < 1.3$	directed flow	WA98 [7]	$0 - 1$ fm

TABLE I: Summary of our findings on the distance  $d_E$  from the present work in comparison to our earlier studies. The Au+Au collisions are taken at  $\sqrt{s_{NN}} = 7.7$  GeV and have intermediate centrality, while the Pb+Pb reactions at  $\sqrt{s_{NN}} = 17.3$  GeV are peripheral. For Ref. [17], the range in rapidity corresponds to  $0.1 < x_F < 0.4$  at the average considered value of  $p_T$ .

section IV. The comparison of our simulation to the data set on Pb+Pb collisions [18] yields the optimal value of  $d_E$  in the range between 0.5 and 1 fm, while the comparison to the data set [7] suggests  $d_E$  in the range from 0 to 1 fm. A more detailed discussion of the two latter comparisons can be found in Refs. [17] and [3], respectively.

In spite of complications arising from the difference in collision energy and centrality between the present work and the two other analyses, a consistent trend is apparent in Table I. At higher values of  $y/y_{\text{beam}}$ , and independently on the considered observable, pions appear to be emitted relatively close to the spectator system, with  $d_E$  remaining below 1 fm. At more central rapidities the pion emission distance increases significantly ( $d_E \approx 3$  fm). This is to be expected for the *longitudinally expanding system* created in the heavy ion collision, where pions at higher rapidity will decouple closer to the spectator as shown in Fig. 6.

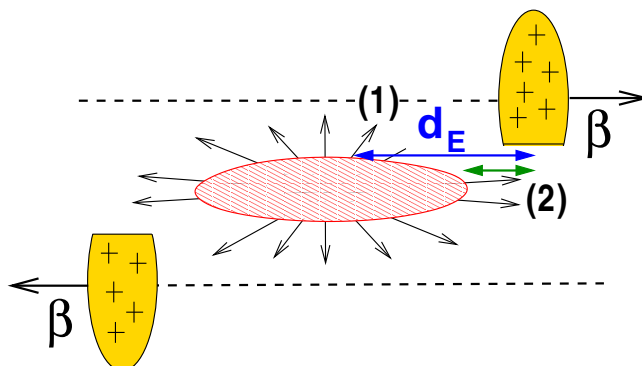


FIG. 6: (Color online) Schematic picture of the longitudinally expanding system created in the heavy ion collision. The distance to the spectator system ( $d_E$ ) is larger for pions emitted at lower rapidity (1) than for pions emitted at higher rapidity (2).

The above observations bring, in our view, important consequences. For the first time, information on the space-time characteristics of this longitudinally expanding, strongly-interacting system responsible for particle production is being provided *by means of the spectator-induced electromagnetic interaction*. This information remains *completely independent* from that provided by femtoscopic analyses [19] or combined blast-wave model fits [20]. Also, as the latter electromagnetic interaction is, by itself, model-independent, this gives hope for a reduction of uncertainties currently present in our knowledge of the expanding

matter created in heavy ion collisions, and for a verification of existing phenomenological models of non-perturbative pion production.

As it is evident from Table I, information provided by the spectator-induced electromagnetic interaction is not confined to any specific region of pion rapidity. On the contrary, it can be used anywhere down from the central (“mid-rapidity”) region up to and beyond beam rapidity. While our present analysis still remains simplified and quite rudimentary, already at the present moment it seems clear that more detailed simulations can bring new insight into the complete  $(x, y, z, t)$  distribution of the pion emission zone drawn in Fig. 6.

## B. Comments on other possible effects

While the aim of this paper is to clarify the role of the electromagnetic interaction between spectators and final state pions in the charge splitting of pion directed flow, some other possible electromagnetic effects should also be commented upon. A first, evident candidate is the electromagnetic interaction induced by the participant charge rather than the spectator charge. For intermediate centrality Au+Au collisions measured by the STAR Collaboration which constitute the basis for the analysis made here, it cannot be *a priori* excluded that the considerable net participant charge will also exert some influence on the observed charge splitting of directed flow. This effect, neglected in our analysis, should in principle be taken into account in future, more detailed studies. On the other hand, we note that the issue of participant charge was studied and commented upon in Ref. [2], in the context of magnetically-induced electric currents acting in the QGP and of their influence on the charge splitting of directed flow. Here, the authors found that the role of participant charge was small (maximally 10%) w.r.t. that induced by the spectator charge.

The work [2] cited above touches another, very interesting problem which necessitates a comment in view of the results obtained in the present analysis. Studying the electric currents induced in the QGP, the authors conclude that the latter result in a charge-dependent directed flow. The results presented in Ref. [2] for positive (negative) pions show this directed flow as mostly negative (positive) at positive rapidity, which is qualitatively similar to our results presented in Figs 4 and 5. The magnitude of the effect strongly depends on pion transverse momentum; limiting our considerations to the range discussed in the present paper,  $0 < p_T < 1.6$  GeV/c, the curves presented in [2] reach maximal absolute values of  $v_1 \approx 0.00004$  at  $p_T = 1$  GeV/c for Pb+Pb collisions at the LHC energy  $\sqrt{s_{NN}} = 2.76$  TeV, and of  $v_1 \approx 0.00012$  at  $p_T = 1$  GeV/c for Au+Au collisions at top RHIC energy,  $\sqrt{s_{NN}} = 200$  GeV (both collisions are considered at 20-30% centrality). This is in principle well below the magnitude of charge-dependent directed flow which we obtained from the STAR data at  $\sqrt{s_{NN}} = 7.7$  GeV (up to about 0.002, see section II, Fig. 2). However, the authors of [2] expect the effects of magnetic fields to increase with decreasing collision energy, and point at the low energy STAR data as showing hints of the phenomena that they had described.

These constataions call, in our view, for a detailed scrutiny in the context of our results obtained in section IV. Indeed, our work suggests that the electromagnetic interaction between spectators and final state pions is, alone, sufficient to explain the charge splitting of directed flow present in the STAR data [6], with no apparent necessity to involve phenomena related to the electric conductivity of the quark-gluon plasma. This was demonstrated in Fig. 4 and most of all in Fig. 5. As we take our electromagnetic effect on final state pions as a straight-forward and *unavoidable* consequence of the presence of spectator charges

in the collision, it seems to us that this effect must be considered as a baseline whenever postulating any more sophisticated phenomenon as the one discussed in [2].

More detailed studies, involving in particular also the energy dependence of our effect on final state pions, are necessary in order to get more insight into the possible interplay between these two effects as a function of collision centrality and energy<sup>4</sup>.

## VI. SUMMARY AND CONCLUSIONS

To the best of our knowledge, the present work was the first analysis of the role played by the spectator-induced electromagnetic interaction in building up the directed flow of charged final state pions produced at central rapidities. This analysis was limited to the spectator-final state pion EM interaction and did not include more sophisticated phenomena related to the electrical conductivity of the quark-gluon plasma. On the basis of our numerical simulation, and assuming intermediate centrality Au+Au collisions at  $\sqrt{s_{NN}} = 7.7$  GeV, we conclude that the spectator-induced electromagnetic interaction can result in a charge splitting of  $\pi^+$  and  $\pi^-$  directed flow which will come on top of phenomena resulting from the strong interactions (Eqs. 2.1, 2.2).

The magnitude of this charge splitting appears to strongly depend on the actual distance between the pion emission site (pion at freeze-out) and the spectator system. As such, this effect brings new, independent information on the space-time evolution of pion production.

In the extreme case of “immediate” pion production, the spectator-induced electromagnetic interaction would induce a maximal charge splitting of  $v_1^{\pi^+}$  and  $v_1^{\pi^-}$  which could reach up to  $2 \cdot 0.025 = 0.05$  in the considered range of rapidity (as apparent in Fig. 4). The charge-dependent component of directed flow, extracted from the experimental STAR data [6] and fairly well described by our simulation, suggests a much lower value for this charge splitting, up to about  $2 \cdot 0.002 = 0.004$  (as apparent in Fig. 5).

Adjusting our simulation to fit the experimental STAR data, and from the comparison of the present analysis to our earlier studies made for pions at higher rapidity, we formulate conclusions on the evolution of the pion emission distance as a function of rapidity. The distance between the pion emission at freeze-out and the spectator system appears to decrease with increasing pion rapidity, reflecting the longitudinal expansion of the system. Thus for the first time, information on the space-time characteristics of the strongly-interacting system created in the collision is being provided by means of the spectator-induced electromagnetic interaction.

Finally, we comment on the effects of electric currents induced in the QGP and studied in Ref. [2]. The magnitude of our EM effect on final state pions being largely sufficient to describe the charge splitting of directed flow apparent in the STAR data [6], we think that this effect should be taken as a baseline whenever considering any more sophisticated phenomenon like the one discussed in [2]. Further, more advanced studies are needed in order to differentiate between these two effects.

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<sup>4</sup> Similarly to phenomena described in [2], we also expect our effect to increase with decreasing energy.

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